

# Discovery of a Second Kilohertz QPO in the X-ray Binary 4U 1735–44

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## ABSTRACT

In recent observations with the Rossi X-Ray Timing Explorer we have detected two simultaneous quasi-periodic oscillation (QPO) peaks in the low mass X-ray binary and atoll source 4U 1735–44. The lower and higher frequency QPOs have frequencies varying between 632 and 729 Hz, and 982 and 1026 Hz, respectively. The fractional rms amplitudes are 3.7 to 8.1% and 5.0 to 5.8%. The frequency separation between the two QPOs changes from  $341 \pm 7$  Hz to  $296 \pm 12$  Hz. The inferred mass accretion rate during our observations is relatively low compared to that during the previous observations, where only a single QPO was present. There is weak evidence that the frequency of the QPOs correlates with the mass accretion rate, as observed in other binaries. Five X-ray bursts were recorded with no detectable oscillations with upper limits for the rms fraction of 4% to 13%.

*Subject headings:* accretion, accretion disks — black holes — stars: individual (4U 1735–44) — stars: neutron — X-rays: stars

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## 1. Introduction

Observations with the Rossi X-Ray Timing Explorer (RXTE) have shown that many low-mass X-ray binaries with neutron stars exhibit oscillations in their X-ray flux at frequencies near 1 kHz (for reviews and references see van der Klis 1998, Swank 1998). It is not clear how the kilohertz QPOs are produced, but they most likely originate very close to the neutron star.

Typically two QPO peaks are simultaneously observable in the the persistent X-ray emission. Early data suggested that only a single QPO was present in some binaries. Further observations, however, revealed a second QPO peak in most cases; an example is 4U 1608–52 (Berger et al. 1996, Méndez et al. 1998c). The only current exceptions are 4U 1735–44 (Wijnands et al. 1998) and Aql X-1 (Zhang et al. 1998a) which have shown only one QPO. Here we show that 4U 1735–44 in fact exhibits two QPO peaks.

In addition to the double QPOs present in the persistent emission of X-ray binaries there is one nearly coherent oscillation seen during some X-ray bursts. The presence of three distinct QPOs in some of these X-ray binaries offers the most intriguing clue yet to the physical mechanisms at work. In four cases the difference in frequency between the persistent QPOs is close to the frequency of the oscillation during the bursts or close to half that value. The simple interpretation is that the burst oscillation is a modulation from the spin of the neutron star, the highest frequency QPO represents a Keplerian frequency, and a beat-frequency mechanism (Alpar & Shaham 1985, Strohmayer et al. 1996) accounts for the lowest frequency QPO.

This interpretation has recently been called into question by new data. The frequency difference of the double QPOs is actually not constant in both the Z-source Sco X-1 (van der Klis et al. 1997) and the atoll source 4U 1608–52 (Méndez et al. 1998a). Furthermore, in 4U 1636–53, the frequency of the burst oscillations does not exactly match the frequency difference (Méndez et al. 1998b). This casts doubt on the beat-frequency mechanism or at least complicates such a model. Further observations of systems with double QPOs and X-ray bursts are clearly desirable.

The RXTE observations of 4U 1735–44 in this paper were obtained by a trigger designed to capture this source at a relatively low mass accretion rate. In

Section 2 we present our observations and results. In Section 3 we discuss the QPO properties in the context of other measurements.

## 2. Observations & Results

In May 1998 we initiated observations of 4U 1735–44 with RXTE based on a low flux measurement by the RXTE All-Sky Monitor. The observations were conducted on 30 and 31 May 1998 and yielded roughly 21 ksec of usable data divided into intervals by the satellite orbit. We generated Fourier power spectra from ‘event mode’ data from the proportional counter array (PCA) with a time resolution of 122  $\mu$ sec. Except where noted, we use the entire PCA energy band, most sensitive from 2 to 30 keV. For color and energy spectral analysis we use the ‘Standard 2’ mode data and eliminate the last of the five detectors which is off during part of the 30 May observation. We perform background subtraction with the version 2.0c of the RXTE background estimator (Stark et al. 1998).

In the May 1998 observations we detect two simultaneous kilohertz QPOs. Figure 1 shows example Fourier power spectra from two intervals. In these spectra the significance of the two QPOs are  $6.4\sigma$  and  $3.7\sigma$  (30 May) and  $17.8\sigma$  and  $4.1\sigma$  (31 May). We report here only detections with a significance greater than  $3\sigma$ . Complete results are summarized in Table 1. The double QPOs are detectable in three separate time intervals. The difference in frequency between the two QPOs has an average value of  $326 \pm 6$  Hz. This value does however change from  $341 \pm 7$  to  $296 \pm 12$  Hz. These values are different with a significance of  $3.1\sigma$ .

The X-ray color-color diagram is shown in Figure 2. For completeness we include the observations from August to October 1996 (Wijnands et al. 1998). The colors and the properties of Fourier power spectra change in a way that is well known for atoll sources (Hasinger & van der Klis 1989). In all the 1996 observations the source is in the ‘banana state’ of the atoll sources (Wijnands et al. 1998). The power spectra show a power law noise component below 1 Hz. In the leftmost part of the banana branch (observations from August 1996) the ‘high frequency noise’ component known in atoll sources is also present with an rms fraction of 3.6% (2–18 keV and 0.01–100 Hz). The observations of 30 and 31 May 1998 sample the source in a different state: the ‘island state’. These data occupy a roughly circular region in the color di-

agram. The power spectra can be described by a broken power law, representing the high frequency noise component. The rms fraction of this component is strongest here,  $6.1 \pm 0.3\%$  to  $6.6 \pm 0.2\%$ . These data represent the most extreme island state yet observed in this source as judged by the strength of the high frequency noise component. The strongest high frequency noise previously observed was  $4.0 \pm 0.4\%$  for similar energies (Hasinger & van der Klis 1989). We do not detect features similar to the 30 or 60 Hz features seen in the 1996 data (Wijnands et al. 1998).

There is evidence that in 4U 1735–44, like other binaries, the source state and the frequencies of the QPOs are related. In the 1996 observations, in the lower part of the banana, there is a QPO at 1144 to 1161 Hz which is most likely the higher frequency QPO (Wijnands et al. 1998). In the present data, an island state, the frequency of this QPO is 982 to 1026 Hz.

We have also analyzed the energy spectra. Fitting the spectra with an absorbed blackbody plus power law components, we find a total absorbed X-ray flux of  $3.2 - 5.6 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$  (2–20 keV). The lowest fluxes are from the island states in May 1998, while the highest fluxes are in the banana state from 1996. The corresponding luminosity is  $3.2 - 5.6 \times 10^{37} \text{ erg s}^{-1}$  for a distance of 9.2 kpc (Van Paradijs, Penninx & Lewin 1988), making 4U 1735–44 one of the most luminous atoll sources to show kilohertz QPOs.

There are five X-ray bursts in the 30 May 1998 observations. We detect no oscillations in any of the bursts, searching Fourier power spectra from both the full PCA energy band and the 2 to 5 keV band. We find upper limits of 4% to 7% for the full band (the better limits being at the peak of the burst) and 8% to 13% for the 2 to 5 keV band. These limits are much smaller than the amplitudes of bursts oscillations observed in other sources, but similar to the upper limits in bursts where there are no oscillations (Strohmayer, Zhang & Swank 1997).

### 3. Discussion

We have discovered a second kilohertz QPO in 4U 1735–44 and observed a link between the QPO properties and the inferred mass accretion rate. 4U 1735–44 was one of only two sources in which only a single QPO had been securely detected. The separation in frequency between the two QPOs decreases with increasing inferred mass accretion rate. The change

has a  $3.1\sigma$  significance. The average frequency separation is  $326 \pm 6 \text{ Hz}$ , similar to the value observed in other low-mass X-ray binaries. Under the simple beat-frequency interpretation of the QPOs the frequency difference would equal to the spin frequency of the neutron star. This interpretation, however, is called into question by an observed change in the frequency separation. The frequency separation also changes in Sco X-1 (van der Klis et al. 1997) and 4U 1608–52 (Méndez et al. 1998a), becoming smaller at higher accretion rates. If any burst oscillations are detected in future observations, the beat frequency prediction can be tested. There is strong motivation for such measurements given the recently noted discrepancy in these frequencies in 4U 1636–53 (Méndez et al. 1998b).

The present data also show a link between the properties of the QPOs and the the inferred mass accretion rate. This is illustrated most clearly in Figure 2. The mass accretion rate likely increases going from the ‘island’ to the ‘banana’ states as shown by the arrow. The QPOs are present only at the relatively lower mass accretion rates. At the lowest accretion rates there are two QPOs, while at slightly higher rates there is one QPO. At the highest rates there are none.

This fits into a general pattern seen in atoll sources. 4U 1820–30 has a similar color diagram and the kilohertz QPOs were apparently detected only at intermediate accretion rates (Zhang et al. 1998b). During a recent outburst of 4U 1608–52 the QPOs were detected at the intermediate rates, at the lower end of the banana branch and the island states closet to the banana (Méndez et al. 1998d). Similarly in 4U 1705–440, QPOs are seen only at intermediate accretion rates (Ford, van der Klis & Kaaret 1998). At the highest accretion rates, farthest into the banana branches, the QPOs are absent as seen in numerous sources: 4U 1636–53 (Zhang et al. 1996; Wijnands et al. 1997), 4U 1820–30 (Smale, Zhang & White 1997, Zhang et al. 1998b), KS 1731–260 (Wijnands & van der Klis 1997), and 4U 1705–440 (Ford, van der Klis & Kaaret 1998). In these high states the upper limits are quite strong (typically 2 to 4% rms). In the island states, which have lower count rates, the upper limits are less stringent. On certain occasions QPOs have been detected in island states in the following sources: 4U 0614+091 (Méndez et al. 1997), 4U 1608–52 (Yu et al. 1997, Méndez et al. 1998d) and 4U 1728–34 (Ford & van der Klis 1998, Strohmayer et al. 1996).

The mass accretion rate is linked not only to the presence of the QPOs but to their frequencies as well. In the present data the frequency of the QPO is highest in the banana state. The data are insufficient however to quantitatively distinguish a correlation of the QPO frequency with the properties of the noise at lower frequencies. Such a trend is seen in other atoll sources, most notably 4U 1728–34 (Ford & van der Klis 1998). This correlation can be explained by current models for the production of kilohertz QPO (e.g. Miller, Lamb & Psaltis 1997; Titarchuk, Lapidus & Muslimov 1998).

Observations therefore point to a clear link between the presence and properties of the QPOs and the apparent mass accretion rate of a given source. There is, however, no such correlation between sources. For example 4U 1735–44, 4U 1608–52 and 4U 0614+091 are each separated by about a decade in luminosity, nevertheless the QPO properties are nearly identical. This is the most enigmatic observational fact about kilohertz QPOs.

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TABLE 1  
4U 1735–44 MAY 1998 OBSERVATIONS

Observation (1998)	$T$ (sec)	$R$ (counts s <sup>-1</sup> )	Frequency (Hz)	$\Delta\nu$ (Hz)	FWHM (Hz)	rms (%)
30 May 7:50:23	3506	1308	981.7 $\pm$ 6.7 640.5 $\pm$ 2.5	341.2 $\pm$ 7.2	32 $\pm$ 7 53 $\pm$ 20	5.3 $\pm$ 0.7 6.2 $\pm$ 0.5
30 May 9:25:20	1351	1282	631.9 $\pm$ 6.3		38 $\pm$ 20	5.9 $\pm$ 0.7
30 May 9:49:38	1710	1299	633.3 $\pm$ 5.7		39 $\pm$ 14	5.4 $\pm$ 0.8
30 May 11:01:19	3740	1358	709.5 $\pm$ 0.4		23 $\pm$ 2	7.5 $\pm$ 0.3
30 May 12:38:33	2983	1376	1025.0 $\pm$ 12.3 728.6 $\pm$ 0.3	296.4 $\pm$ 12.3	84 $\pm$ 47 9 $\pm$ 2	5.0 $\pm$ 1.0 7.2 $\pm$ 0.2
31 May 11:01:19	3767	1376	1025.7 $\pm$ 17.0 725.5 $\pm$ 0.8	300.2 $\pm$ 17.0	135 $\pm$ 43 24 $\pm$ 2	5.8 $\pm$ 0.8 8.1 $\pm$ 0.3
31 May 12:37:19	3807	1364	716.9 $\pm$ 0.6		21 $\pm$ 1	3.7 $\pm$ 0.9

NOTE.— The start time of each observation is in UTC (Universal Time, Coordinated).  $T$  is the duration of the observation.  $R$  is the count rate background subtracted over the full PCA energy band for 5 PCUs. The QPO frequencies, FWHM and rms fraction are listed as calculated using data of the entire PCA energy band.  $\Delta\nu$  is the frequency difference between double QPOs. Errors are statistical using  $\Delta\chi^2 = 1$ .

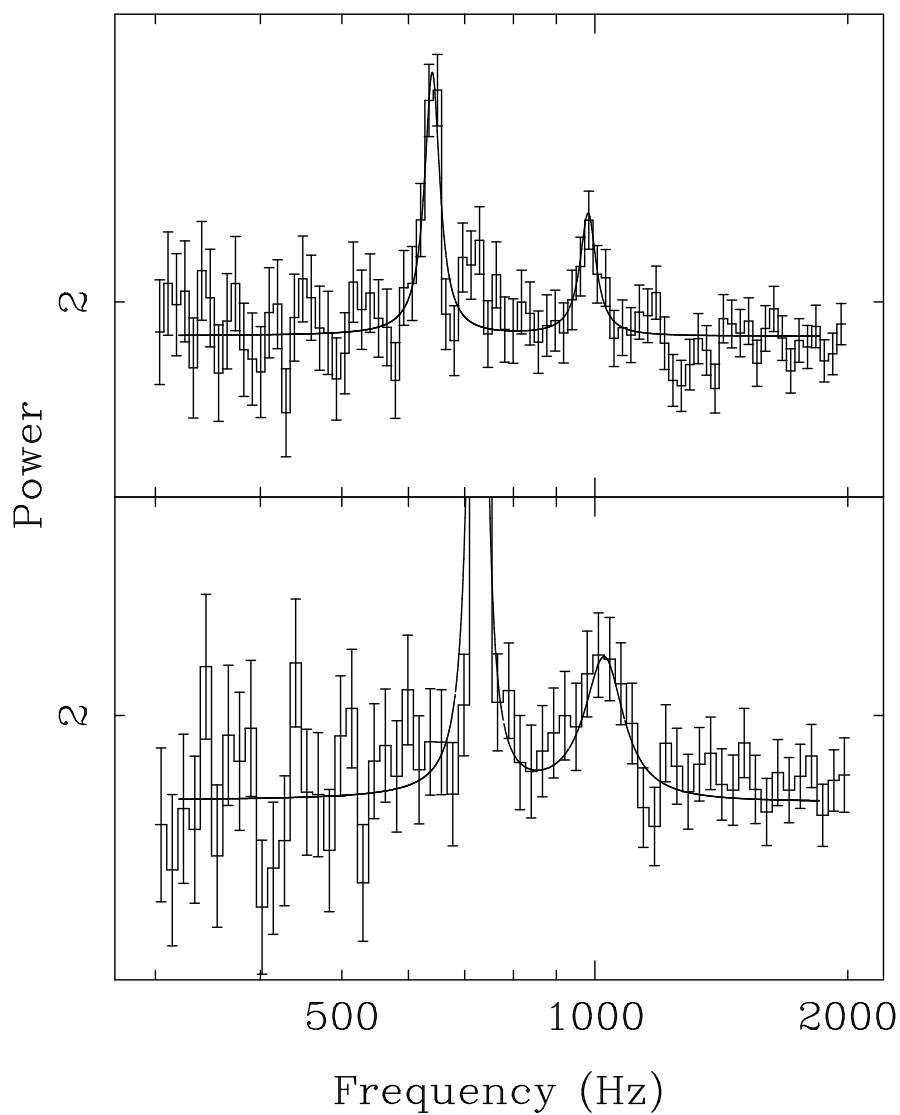


Fig. 1.— Power density spectrum for observations starting 30 May 1998 7:50:23 (top) and 31 May 11:01:19 UTC (bottom). The lower frequency peak of 31 May is off-scale. See Table 1 for more information.

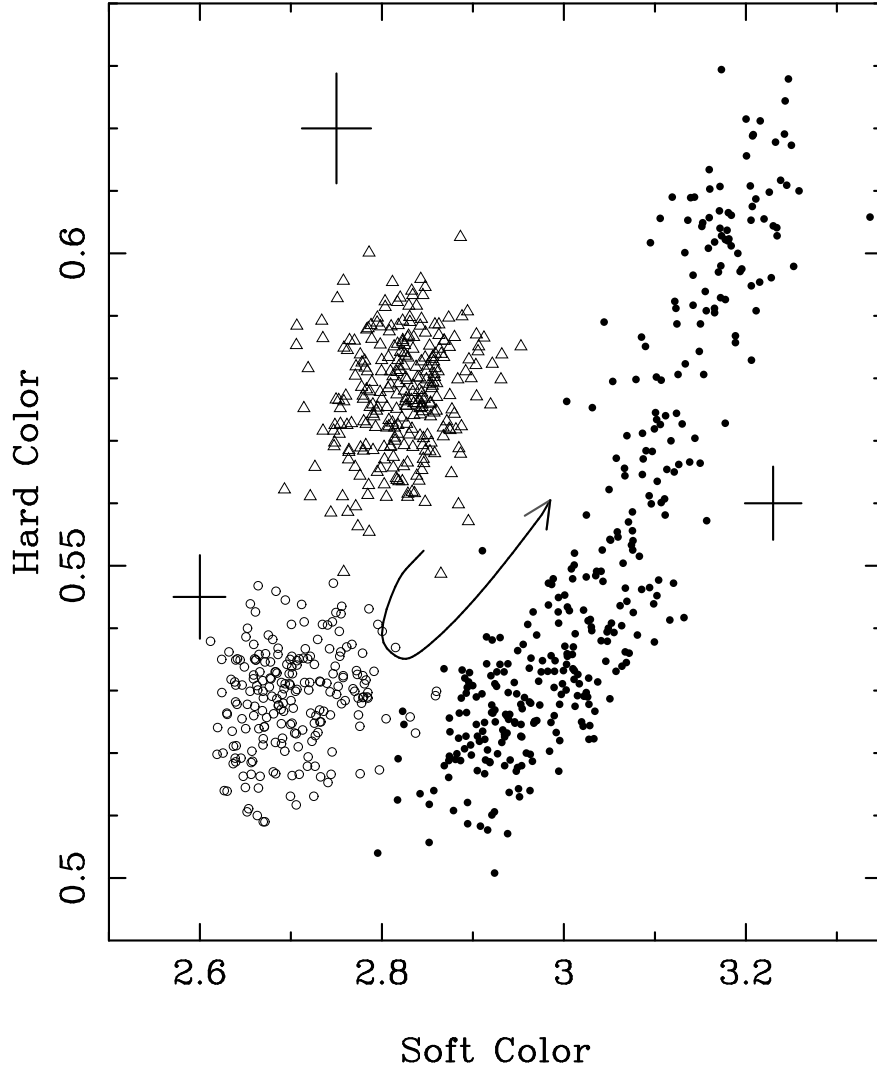


Fig. 2.— X-ray color-color diagram of 4U 1735-44. The data symbols are: May 1998 (triangles), 1 August 1996 and 28 September 1996 (open circles), and 1 and 4 September 1996 and 29 October 1996 (filled circles). The arrow shows the direction of increasing inferred mass accretion rate. Colors are defined by ratios of PCA count rates in the bands 3.4–6.3/2.0–3.4 keV (soft color) and 9.6–15.7/6.3–9.6 keV (hard color). Data points are 48 second time bins from the first four detector units with background subtraction. Typical errors are shown.